Cornering Solar Radiative-Zone Fluctuations with KamLAND and SNO Salt

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We update the best constraints on fluctuations in the solar medium deep within the solar Radiative Zone to include the new SNO-salt solar neutrino measurements. We find that these new measurements are now sufficiently precise that neutrino oscillation parameters can be inferred independently of any assumptions about fluctuation properties. Constraints on fluctuations are also improved, with amplitudes of 5% now excluded at the 99% confidence level for correlation lengths in the range of several hundred km. Because they are sensitive to correlation lengths which are so short, these solar neutrino results are complementary to constraints coming from helioseismology.

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INTRODUCTION

Neutrino-oscillation measurements are entering an era of unprecedented precision, with the solar neutrino data [1, 2, 3] and atmospheric neutrino data [4, 5] combining to give a concordant picture of conversions amongst three species of active neutrinos [6, 7]. The oscillation parameters which describe these conversions are the two mass-squared differences, $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$, the three mixing angles, θ_{12}, θ_{23} and θ_{13}, plus phases which violate CP [8] and are still to be probed. The best fits to these parameters are consistent with a maximal atmospheric mixing angle, θ_{23}, and give a preferred solar mixing angle in the so-called large mixing angle (LMA-MSW) regime [9]. The third angle, θ_{13}, is strongly constrained mainly by reactor experiments [10].

A crucial recent development has been the verification of these oscillation parameters in purely terrestrial measurements, with the KamLAND experiment [11] reporting measurements which are consistent with the oscillation parameters indicated by the solar neutrino analysis. Such an independent measurement of oscillation properties is invaluable since it allows a cleaner separation to be made between neutrino properties and solar physics, thereby opening a new observational window deep into the solar interior [12].

In particular, the precise terrestrial observation of oscillations relevant to solar neutrinos allows the removal of a theoretical uncertainty in the inference of neutrino properties. This uncertainty arises because specific types of fluctuations of the solar medium deep within the solar radiative zone are known to affect neutrino oscillations [13, 14, 15, 16], if they have sufficient size. Consequently the inference of neutrino properties from solar data require the use of prior assumptions concerning these such fluctuations.

Traditionally, the necessity for making these prior assumptions concerning solar fluctuations has not been regarded as being worrisome for several reasons. First, helioseismic measurements can constrain deviations of solar properties from Standard Solar Model predictions at better than the percent level. Second, preliminary studies of the implications for neutrino oscillations of radiative-zone helioseismic waves [16] showed that they were very unlikely to have observable effects. Third, no other known sources of fluctuations seemed to have the properties required to influence neutrino oscillations.

All three of these points have been re-examined in recent years, with the result that the presence of solar fluctuations seems more likely than previously thought. First, direct helioseismic bounds turn out to be insensitive to fluctuations whose size is as small as those to which neutrinos are sensitive [17, 18] (which, as we argue below, turn out to be those whose size is only several hundreds of km). Second, recent studies of magnetic fields deep inside the solar radiative zone [19] have identified potential fluctuations to which neutrinos might be sensitive after all (due to a resonance between Alfvén waves and helioseismic g-modes).

These studies motivate us to investigate again the extent to which neutrino-oscillation parameters can be extracted independent of prior assumptions concerning the solar fluctuations. In principle, sufficiently precise separate measurement of oscillation parameters by KamLAND and by solar neutrino detectors may allow this type of prior assumption to be relaxed. Unfortunately, global fits to the post-KamLAND data in the presence of fluctuations [20, 21] have indicated that the data were not yet sufficiently precise to allow the neutrino-oscillation parameters and the solar fluctuations to be disentangled with good accuracy.

The recent release of the SNO salt results [22] call for a

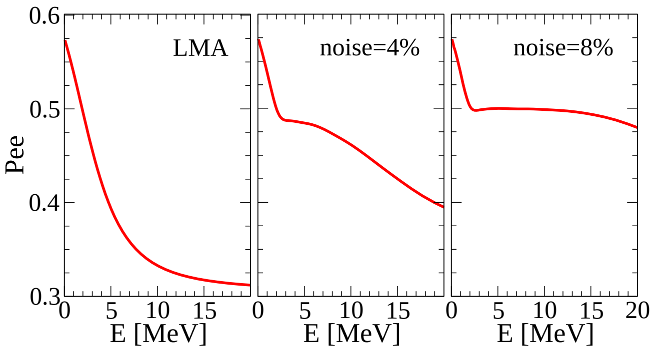

Figure 1: Effect of random electron density fluctuations on electron-neutrino survival probability for LMA-MSW oscillations and a correlation length $L_0 = 100$ km. The fluctuation's amplitude ξ at the position of neutrino resonance is zero in the left panel, and is $\xi = 4\%$ and $\xi = 8\%$ in the middle and right panels, respectively.

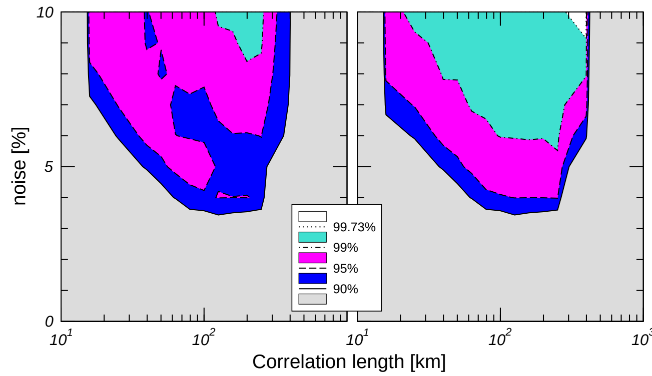

Figure 2: Exclusion region in the amplitude–correlation length ($\xi - L_0$) plane for solar fluctuations using KamLAND and solar neutrino data before the SNO–salt experiment. In the right panel the neutrino oscillation parameters are assumed known while both oscillation and fluctuation parameters are jointly fit in the left panel. The lines indicate contours of 90, 95, 99% CL and 3 σ.

re-evaluation of this conclusion, since these considerably improve the precision with which solar neutrino properties are determined. It is the purpose of the letter to show that with these new data solar neutrino measurements have now changed the picture, inasmuch as global fits to neutrino properties no longer need to make prior assumptions about solar medium fluctuations in order to infer neutrino oscillation parameters. We also summarize the direct constraints on these fluctuations which may now be convincingly inferred for the first time, without making prior assumptions concerning the details of neutrino oscillations. Finally we forecast the precision which will be possible to achieve with subsequent terrestrial neutrino measurements.

SENSITIVITY TO FLUCTUATIONS

The standard description of MSW oscillations [23] amount to the use of a mean-field approximation for the solar medium. The corrections to this mean-field approximation are due to the fluctuations in the solar medium about this mean, and the leading interaction of neutrinos with these fluctuations are parameterized by the electron-density autocorrelation, $\langle \delta n_e(t) \delta n_e(t') \rangle$, measured along the neutrino trajectory [13, 14, 15, 16].

As fig. (1) shows, such fluctuations act to degrade the efficiency of neutrino conversions. They can do so because successive neutrinos 'see' slightly different solar properties, and so in particular do not experience an equally adiabatic transition as they pass through the neutrino resonance region. The net effect is to degrade the effectiveness of the neutrino conversion because those neutrinos for which the transition is less adiabatic are more likely to survive as electron-type neutrinos. Since criterion for the transition to be adiabatic depends on how quickly the electron distribution varies near resonance, fluctuations give observable effects for neutrinos if they occur at resonance with sufficient amplitude, and if their correlation length, L_0, is comparable to the local neutrino oscillation length, $L_{\rm osc} \sim 100$ km.

THE IMPLICATIONS OF THE SNO SALT RESULT

We now report on the result of fits which are obtained using a global analysis of the solar data, including radiochemical experiments (Chlorine, Gallex-GNO and SAGE) [1] as well as the latest SNO data in the form of 17 (day) + 17 (night) recoil energy bins (which include CC, ES and NC contributions, see [24]) [2] and the Super-Kamiokande spectra in the form of 44 bins [3] (8 energy bins, 6 of which are further divided into 7 zenith angle bins). We have also used the improved measurement with enhanced neutral current sensitivity due to neutron capture on salt, which has been added to the heavy water in the SNO detector. The data are presented in the form of the neutral current (NC), charged current (CC) and elastic scattering (ES) fluxes [22]. Following Ref. [26] we used data from the KamLAND collaboration given in 13 bins of prompt energy above 2.6 MeV [11].

The sensitivity of the solar neutrino data to fluctuations in the solar medium is summarized by figures (2) and (3). Fig. (2) is taken from ref. [20], and summarizes the sensitivity before the SNO salt measurements. Fig. (3) gives the same results after SNO salt. Comparing these figures shows the improvement in constraints due to the SNO salt data, and comparing the panels in each figure shows the importance of a precise determination of the neutrino oscillation parameters for obtaining a constraint on the magnitude of fluctuations.

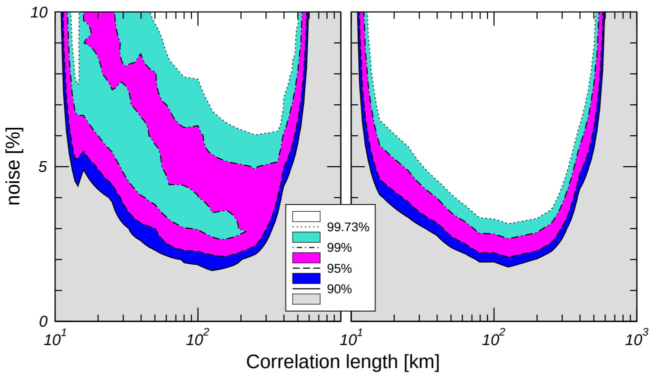

Figure 3: Sensitivity of solar neutrino data to the solar fluctuations including the SNO salt measurements. As in Fig. 2 the right panel assumes the neutrino oscillation parameters are known while the left panel shows the result when both oscillation parameters and fluctuations are jointly fit.

The importance of the KamLAND and the SNO-salt measurements in these results is most easily seen from fig. (4), which compares the dependence of the fit's χ^2 on the amplitude of the fluctuations for various individual data sets. This figure makes clear how the KamLAND results are largely responsible for localizing the best fit near zero fluctuation amplitude. This is as should be expected, since the evidence for the absence of fluctuations follows from the comparison of solar neutrino observations with terrestrial measurements of neutrino oscillation properties.

Note, however, that further precise determination of neutrino parameters at KamLAND due to higher statistics will have a very modest impact on the limit on the amplitude of density fluctuations within the 99% C.L. region, as can be seen from the dot–dashed line in Fig. 4.

Fig. (5) shows how the existence of solar fluctuations influences the determination of the neutrino oscillation parameters, and contains our main result. The two panels of the figure contrast the precision of the fit with and without solar fluctuations. The left panel gives results subject to the usual prior assumption of no solar fluctuations, while the right panel leaves the amplitude of such fluctuations to be obtained from the fit. (When fluctuations are included, they are assumed to have the optimal correlation length $L_0 = 100$ km.) The lines indicate contours of fixed confidence level when the KamLAND data are not included, while the coloured regions give the same information when KamLAND is included.

The main conclusion which follows from this figure is that the precision with which the neutrino oscillations are known is now largely independent of whether a prior assumption is made about the existence of solar fluctuations. With the release of the SNO salt results the comparison of solar neutrino with KamLAND data suffices to robustly determine the oscillation parameters independent of the assumed amplitude of solar fluctuations. The

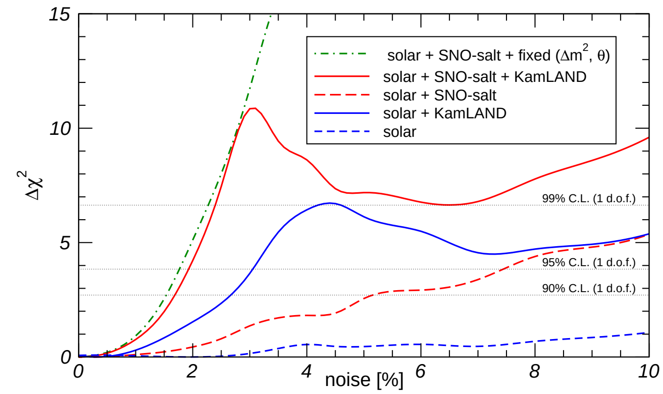

Figure 4: The chi-square of the fit as a function of fluctuation amplitude for a correlation length $L_0 = 100$ km.

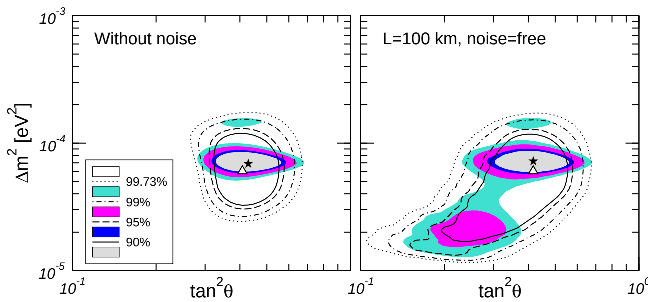

Figure 5: The solar neutrino oscillation parameters obtained in our global fit for $L_0 = 100$ km. The left panel assumes no noise, while in the right panel the amplitude of the noise is left arbitrary. The coloured regions are obtained using the KamLAND data, while the lines refer to CL contours without KamLAND.

SNO salt data are crucial for reaching this conclusion, as is clear from fig. (6), which compares the right panel of fig. (5) with the same fit performed without using the SNO salt results.

OUTLOOK

We see that the SNO salt data, when combined with KamLAND results, for the first time places the determination of neutrino-oscillation parameters beyond the reach of sensitivity to prior assumptions concerning the existence of fluctuations in the solar radiative zone. Besides making more robust the determination of neutrino-oscillation parameters, this allows a much sharper determination of the kinds of solar fluctuations that may still be allowed deep within the solar radiative zone. As we have seen, the resulting constraints apply to fluctuations whose spatial scales are of order 100 km, and so are complementary to those obtained from helioseismology, which are insensitive to fluctuations on such short scales.

Ref. [19] has suggested one possible mechanism for obtaining observable fluctuations in the relevant part of the

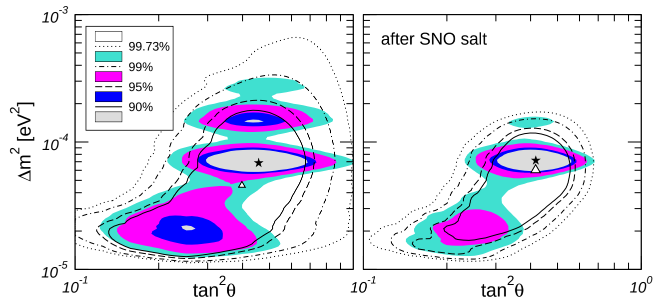

Figure 6: The same fit (including fluctuations) as given in fig. (5), performed with (right) and without (left) the SNO salt results.

sun. In that picture fluctuations having the appropriate distance scale may arise if magnetic fields of order 10 kG should exist deep in the solar core. Magnetic fields of this size would be consistent with current observational bounds [27, 28].

It is instructive to ask how the precision of these results is likely to improve given the new neutrino experiments which are currently being planned. In addition to further statistics from the KamLAND reactor experiment, we expect a high statistics of solar neutrinos above 5 MeV at the UNO experiment, which would make solar precision measurements possible [29]. Quantifying the sensitivity of upcoming detectors as probes of the Sun deep within the radiative zone lies outside the scope of this note.

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